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Iot-based smart agricultural watering robot using fuzzy-PID hybrid control

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Abstract

Precision agriculture has been revolutionized through the integration of IoT and smart control systems, particularly in automated irrigation and robot navigation. Inefficiency, wastage of water, and lack of environmental adaptability are some of the typical problems related with conventional irrigation systems. This work designs an IoT-Based Smart Agricultural Watering Robot based on a Fuzzy-PID Hybrid Control to improve water distribution and robot navigation. The proposed prototype attains 94.3% tracking accuracy, 91.75% success rate in obstacle elimination, and 39.5% efficiency in water conservation. The system greatly augments agricultural efficiency by incorporating real-time sensor data, fuzzy logic (FL) for decision-making, and PID control for accurate movement. This innovation is vital for enhancing irrigation management and reducing resource waste, which makes it a promising solution for precision agriculture.

Keywords*:* IoT; Smart Agriculture; Fuzzy Logic; PID Control; Precision Irrigation; Obstacle Avoidance; Sensor-Based Automation; Water Conservation

1. Introduction

IoT infrastructure includes sensors, actuators, communications networks, cloud computing, and data analysis software. Sensors collect current information such as temperature, humidity, movement, or stress, and actuators respond by undertaking activities that have been extracted from data acquired.[1]. In the occupation of sustainable farming practices that enhance productivity with environmental sustainability, the identification of technological solutions is essential. A development of the farming process through state-of-the-art IoT-based automation will most possibly result in a positive economic influence along the market chain, ranging from producers to consumers. The innovation and maintenance of these technologies will produce new opportunities in the farming industry, driving future innovation and productivity.[2], [3]. Based on real-time environmental information soil moisture, temperature, and humidity, this framework takes accurate watering decisions that enhance water efficiency and boost healthy crops[4]. Through the amalgamation of PID control with FL, irrigation can be tuned and stable in response to environmental incertitude, while also ensuring accurate flow management[5].

When faced with uncertain, imprecise, ambiguous conditions, FL is a strongly implied method of decision-making[6]. It gives an effective means of coping with such complexity and can verify to be a valuable tool in numerous situations, particularly in smart farming[7]. We develop an IoT-based smart agriculture watering robot in this research, which appliances FL along with PID control to enhance irrigation based on sensor data in real-time[8]. The system supervises soil moisture, temperature, and humidity to decide adaptive watering, thus making effective use of water[9]. This approach improves automation, sustainability, and fertility of crops in modern precision agriculture by ratifying FL for ambiguity handling and PID control for precise regulation[10] [11].

Most existing irrigation systems are often based on autonomic PID controllers or fixed-rule automation, which are not effective in adaptation to changing environmental conditions and thus cause water wastage and inefficient crop

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management. Even those IoT-based solutions that execute machine learning require high computational power and large datasets, making them less practical for real-time usage. In this work, Fuzzy-PID hybrid control is combined to overcome these constraints, comprising FL for adaptive decision-making and PID control for accurate water regulation. The system fortifies efficient irrigation, condensed water consumption, and enhanced crop health by utilizing real-time sensor inputs and IoT connectivity, making it a scalable and cost-effective solution for precision agriculture.

1.1. Problem Statement:

conventional irrigation techniques often suffer from inefficient water utilization, over-irrigation, or under-irrigation, lead to loss of water, soil erosion, and lower crop yield. Existing computer-based automated irrigation systems lack adaptive decision-making mechanisms, which makes them unable to cope with ambiguity and unpredictability of environmental conditions[12] [13].traditional PID controllers conflict to make dynamic alterations in irrigation levels based on soil moisture, temperature, and humidity changes[14]. This research intends an IoT-based smart agriculture watering robot that combines FL and PID control to provide real-time, accurate, and adaptive irrigation, thus improving water conservation, crop health, and sustainable farming practices to address these challenges[15].

Objectives:

- Design a smart farm watering robot using IoT for real-time monitoring and automated water supply.
- Implement FL and PID control to achieve adaptive and precise water distribution based on sensor inputs.
- Optimize water usage and enhance crop health through dynamic irrigation management in response to environmental conditions.
- Integrate IoT connectivity for remote monitoring and management, improving farm efficiency and sustainability.

2. Literature review

Gudivaka.et.al., suggested IIoT-based Condition Monitoring System (CMS) is intended to detect bad bearings before they come to a critical state when in rotation[16]. Basani emphasized the need for accurate and efficient item identification towards the automation of logistics, inventory control, and assembly lines, especially with the trend of rising IoT use[17]. Grandhi introduced a new event-based processing strategy with the purpose of enhancing the scalability, accuracy, responsiveness, energy efficiency, and cost-effectiveness of IoT applications[18],[19]. This mechanism enables microcontrollers to conserve energy while remaining responsive[20]. Sareddy.et.al., highlighted the advantages of integrating advanced models into HR functions for improving decision-making, workforce planning, employee retention, and overall productivity[21]. The use of AI-powered robotic systems in rehabilitation—particularly in terms of grip strength, dexterity, and motor function—was also discussed by Gudivaka.et.al., They noted, however, that there is limited extensive research on how to integrate robotics and AI in the entire rehabilitation process[22].

Grandhi researched the integration of Human-Machine Interface (HMI) display modules with passive IoT optical fiber sensor networks for enhanced water level monitoring, using Fiber Bragg Grating (FBG) sensors to visualize real-time data and manage the environment[23],[24]. Raj Kumar Gudivaka.et.al., presented an algorithm for generating optimal collision-free paths in barrier-filled environments using deterministic CME for cost and utility evaluation, thus improving robot navigation[25]. Basani examined the historical evolution of AI in cybersecurity, investigating critical AI technologies, supporting existing systems, and their impact on cyber resilience[26], [27]. The research highlights the growing importance of IoT, AI, and sensor networks in automated decision-making, environmental monitoring, and secure, efficient robotic operation, which corresponds to smart agricultural automation's objectives[28], [29].

Raj Kumar Gudivaka.et.al., discussed the challenges involved in evaluating classification frameworks, pointing out that when models or human expertise are being compared, an important performance measure is classification accuracy[30],[31]. Grandhi.et.al., suggested a predictive maintenance strategy for EV components which combines optical and quantum methods with Fiber Bragg Grating (FBG) sensors to gather high-resolution real-time information regarding batteries, electric motors, and power electronics with a focus on their sensitivity and resistance to electromagnetic interference[32],[33]. Sareddy examined the role of AI and ML in handling workforce, with a focus on staffing, scheduling, performance evaluation, talent acquisition, and skill building[34]. Collectively, these research emphasize the importance of AI, sensor networks, and classification techniques in automation that aligns with the objectives of smart agriculture by driving predictive analytics, decision-making, and system efficiency[35].

Gudivaka researched the integration of Principal Component Analysis (PCA), Least Absolute Shrinkage and Selection Operator (LASSO), and Elaborative Stepwise Stacked Artificial Neural Network (ESSANN) to enhance IoT and robotic process automation (RPA) systems, enhancing data pre-processing, feature selection, and predictive modeling for the management of intricate datasets[36]. Rajya Lakshmi Gudivaka.et.al., presented a secure encryption system that combines RSA and AES encryption to ensure data redundancy, confidentiality, and integrity, as well as protection against cloud-based attacks[37]. Basani introduced an AI-powered robotic delivery system with advanced authentication methods[38]. The methods involve PIN codes, biometric verification, and AI-based facial recognition to guarantee safe identification of recipients[39]. The research points towards the significance of AI, encryption, and automation in supporting security, decision-making, and operating efficiency. It aligns with IoT-based intelligent agriculture objectives through the improvement of data management, predictive control, and system dependability[40].

3. Proposed methodology

IoT, sensor-based monitoring, and smart control methods are employed to automate farm watering and robotic navigation. The environment data like moisture content, temperature, rain, air quality, and obstruction detection are captured through an array of sensors. Kalman filtering is applied for noise elimination and accuracy in sensors. The processed data is then handled by a rule-based FL system to determine the irrigation needs and robot motion.

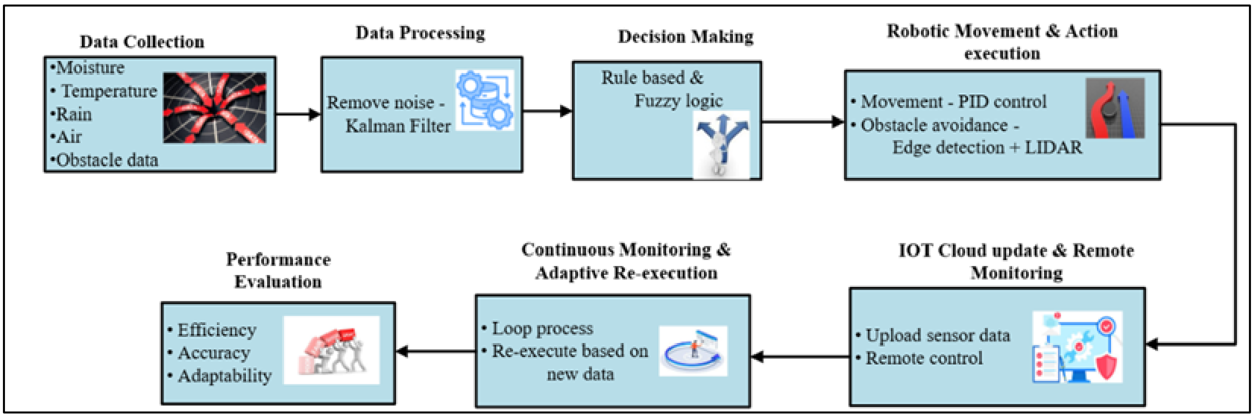

Figure 1 IoT-Based Smart Irrigation and Robotic Control

The robot's motion is controlled using a PID controller for smooth and unrestricted movement and obstacles are detected using edge detection and LiDAR. The processed data are transmitted to an IoT cloud to be remotely monitored and controlled. Through continuous monitoring, processes can be retried in real time, making smart farming efficient, precise, and responsive.

3.1. Data Collection & Sensor Inputs:

Multiple sensors are used to achieve the proper recording of real-time agricultural data to be used in irrigation and movement of robots. Soil water content sensors measure the water levels in soil, while temperature and humidity sensors determine climatic elements that affect the need for irrigation. Rain sensor evaluates if artificial irrigation is needed, and an air quality sensor monitors hazardous gases that can affect crops. Ultrasonic and LiDAR sensors help in safe robotic navigation by finding obstacles in the environment. The sensor inputs gathered and provide important parameters for decision-making, allowing optimal water use and improving crop health through dynamic irrigation management.

3.2. Sensor Data Processing Using Kalman Filter:

A Kalman filter is utilized to minimize noise and sensor variation in readings to increase the accuracy of sensor data before making decisions. In order to remove inconsistencies particularly readings of air quality, soil temperature, and moisture the filter makes predictions and upgrades sensor measurements. The state prediction equation is as follows:

$$\hat{z}_{m|m-1} = \hat{P}_{m-1|m-1} + Qv_m \text{.........}(1)$$

$$T_{m|m-1} = PT_{m-1|m-1}P^S + N \text{........}(2)$$

and the update step:

$$M_m = T_{m|m-1} G^S (G T_{m|m-1} G^S + C)^{-1} \quad (1)$$

$$\hat{z}_{m|m} = \hat{z}_{m|m-1} + M_m (X_m - G\hat{z}_{m|m-1}) \quad (2)$$

$$T_{m|m} = (J - M_m G) T_{m|m-1} \quad (3)$$

The Kalman filter ensures reliable input for decision-making by refining sensor readings, allowing the system to respond accordingly to environmental conditions.

3.3. Decision-Making Using Fuzzy Logic for Adaptive Control:

FL is applied for making decisions to resolve environmental conditions uncertainties and to optimize irrigation efficiency. The system defines input variables as soil moisture, temperature, and rain, and output variables as irrigation rate and robot locomotion. Membership functions define soil moisture as {Dry, Normal, Wet}, temperature as {Cold, Warm, Hot}, and rain as {Light, Medium, Heavy}. Decision rules are created based on these vague variables, such as:

- IF Soil Moisture is Dry AND Temperature is Hot → Increase Irrigation Speed
- IF Soil Moisture is Normal AND Rain is Medium → Reduce Irrigation Speed

FL ensures optimal water use and maintains healthy crop conditions by dynamically adjusting the irrigation rate.

3.4. Robotic Movement & Action Execution (Fuzzy-PID Hybrid Control + Obstacle Avoidance):

A fuzzy-PID hybrid control system is used to provide accurate robotic movement and optimal irrigation task execution. The motor speed is controlled by the PID controller, which makes adjustments in accordance with real-time feedback from sensors using the formula:

$$v(t) = K_p h(t) + K_i \int h(t)dt + K_d \frac{dh(t)}{dt} \quad (4)$$

where $h(t)$is the error (difference between target and current position), and $K_p, K_i, K_d$are adjustment parameters. At the same time, the robot utilizes Edge Detection and LiDAR Mapping for obstacle detection, allowing it to detour and safely traverse the field. FL rules regulate the operation of the irrigation system:

•IF soil moisture < 30% → Pump Activation & Move to Dry Area

•ELSE IF soil moisture > 60% → Stop Pump & Proceed to Next Area

Furthermore, a weed detection system is included, where the camera identifies weeds and activates a cutter motor for their removal. With this hybrid control, movement is smooth, irrigation is productive, and navigation is release of obstacles.

3.5. IoT Cloud Update & Remote Monitoring:

Sensor readings are swapped to an IoT cloud platform AWS or Firebase for distant monitoring and management. This permits farmers to consider real-time field conditions, receive alerts, and alter irrigation parameters distantly utilizing a mobile application or web-based interface. IoT integration improves farm productivity and sustainability through the provision of real-time information and alerts, better water resource management.

3.6. Continuous Monitoring & Re-execution:

For effective irrigation and robotic management, the system displays sensor information in real-time and adjusts irrigation decisions based upon changes in the environment. Sensor information is elevated at periodic intervals, and if conditions depart from the optimal limits, the FL control system forward irrigation and movement instructions to bear crop health and minimize water loss.

4. Result and discussions

The performance assessment of the IoT-based smart agricultural irrigation robot specifies its efficiency in automation and accuracy. With a response time of 1.8 seconds, the FL decision system ensures timely adjustments to irrigation. With obstacle avoidance at a 91.75% success rate, the PID-controlled navigation attains an accuracy of 94.3%, ensuring smooth navigation in the field. The water conservation efficiency is 39.5%, maximizing resource utilization. The system has a low cloud upload latency of 1.2 seconds and a high uptime of 99.1%, ensuring reliable remote monitoring and control.

Table 1 Performance Evaluation of Smart Watering Robot

Performance Metric	Measured Value
Decision Response Time (FL)	1.8 s
Navigation Accuracy (PID Control)	94.3%
Obstacle Avoidance Success Rate	91.75%
Water Conservation Efficiency	39.5%
Cloud Upload Latency	1.2s
System Uptime (IoT Monitoring)	99.1%

Upon detection of an obstacle, the speed adjustment of the robot—controlled by a nonlinear PID control—demonstrates a peak overshoot at the onset followed by diminishing oscillations, as shown in Fig. 2, due to the damping effect of the PID controller. The fast oscillations of the system demonstrate its reactivity to obstacles, and its eventual stabilization demonstrates its adaptive control to smooth movement. The robot successfully adjusts its motion to circumvent collisions without compromising optimal crossing in the farm field.

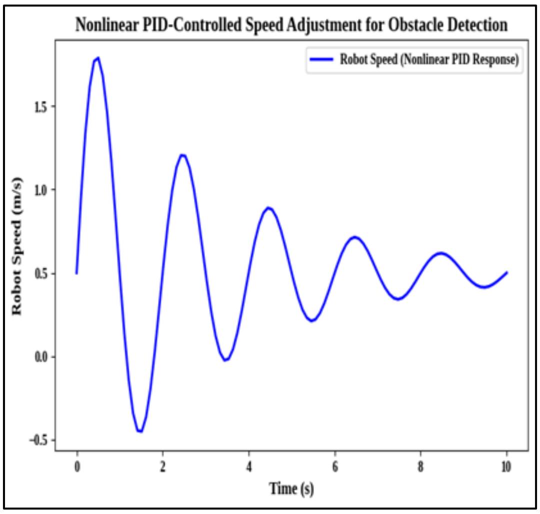

Figure 2 Nonlinear PID-Based Obstacle Detection Response

The PID control parameters used in our IoT-Based Smart Agricultural Watering Robot have been tuned to Proportional Gain (Kp): 1.2, Integral Gain (Ki): 0.5, and Derivative Gain (Kd): 0.3. The above values ensure stable movement, a smooth transition from one speed to another, and effective obstacle avoidance. The above values increase irrigation effectiveness and navigation precision, and the parameters can be further improved to maximize performance for specific environmental situations.

5. Conclusion

The IoT-Based Smart Agricultural Watering Robot utilizes Fuzzy-PID Hybrid Control to augment the accuracy of irrigation and autonomous navigation. The system achieves a 94.3% navigation accuracy, a 91.75% obstacle avoidance success rate, and a 39.5% improvement in water conservation efficiency. In contrast to conventional irrigation techniques, this method reduces water wastage while offering adaptive irrigation based on real-time environmental conditions. The integration of fuzzy logic and PID control enables precise decision-making and smooth movement in robots. Future research will emphasis on AI-based decision-making, merging machine learning for predictive irrigation and adapting the system to large-scale agriculture.

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